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THE TECHNOLOGICAL PROBLEMS OF TELEVISION BROADCAST SATELLITES

by Perry W. Kuhns
Lewis Research Center
Cleveland, Ohio

TECHNICAL PAPER proposed for presentation at Aviation and Space Conference sponsored by the American Society of Mechanical Engineers Los Angeles, California, June 16-19, 1968

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E-4507

ABSTRACT

A television broadcast service is one in which the transmission is intended for direct reception by the general public. Because of the intention of direct reception, there are technological and cost trade-offs between the receiver on the ground and the transmitter in space.

In this paper, the technological level of both the ground receiver and the space transmitter are assessed. The technological problems of the spacecraft subsystems whose characteristics are determined from the trade-offs are discussed. These subsystems include: transmitting antenna, output power amplifier, power conditioning, prime power source, and attitude control and station keeping.

INTRODUCTION

During the past few years, the use of satellites for direct broadcast transmission has become a matter of concern by governmental and private agencies. Typical missions which have been envisioned for such satellites are broadcasting for reception by: homes, schools or professional training groups in industrial nations and training groups or village receivers in developing nations(1, 2).

A television broadcast satellite service is one in which the transmission is intended for direct reception by the general public(3). It is not a relay service. Because of the intention of direct reception by the public, there exists technological and cost trade-offs between the receiver on the ground and the transmitter in space. In assessing the trade-offs, consideration must be given to benefits to be gained and the costs assumed by the public, the government, and industry in the area involved.

The technological and cost factors both on the ground and in space must be assessed and extrapolated into the future. Failure to properly assess the growth in receiver technology can lead to erroneous estimations of the satellite requirements and the economic practicability of satellite broadcast applications. For this reason, both ground and spacecraft technology will be considered in this paper.

Although studies sponsored by the NASA which will help in making better trade-off analyses are only in a preliminary state at present, some observations can be made which have the effect of narrowing the spectrum of applicable spacecraft and services.

(a) From the standpoint of the technological level of the immediate future, a system broadcasting directly to a home receiver with an indoor dipole antenna is out of the question due to the extremely high powers necessary. On all systems considered, external nontracking antennas with an antenna mounted preamplifier and demodulator will be used.

(b) The only orbit for serious consideration is the geostationary orbit.

(c) Evaluation of possible missions has shown that the majority of the satellites would have transmitting antennas with half power beamwidths between 1.0 and 6 degrees with the most probable width in the 3 degree range. The area covered by a 3 degree beamwidth from a stationary orbit is equivalent to the central time zone in the United States.

(d) Two types of modulation should receive prime consideration, vestigial sideband AM of the video signal with FM audio and FM modulation of the video signal with FM-FM modulation of the audio signal.

(e) When considering the total cost of a system including the ground receivers, the ground segment of the cost will be predominant when more than 10^7 receivers are reached and the space segment will determine the cost when less than 10^5 receivers are reached.

Ground Receiver Technology

The preliminary basis for a trade-off between the ground and satellite may be simply stated as: the receiver sensitivity on the ground determines the necessary transmitter power on the spacecraft and power costs weight and money. For a geostationary satellite the average transmitted effective radiated power is given by the proportionality:

ERP (power × transmitter antenna gain)

$$\propto \frac{L \Sigma T_N}{A_R} \times \frac{S/N}{I_T}$$

where:

L is the atmospheric attenuation,

ΣT_N is the total effective noise temperature due to natural and man-made sources, external to the receiver,

A_R is the effective receiving antenna aperture area,

S/N is the desired picture quality, given here as peak signal to rms noise ratio,

I_T is the improvement factor due to FM demodulation or AM power averaging.

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For a typical broadcast satellite application where the receivers number in the millions and with typical assumed values for the parameters the two terms in the brackets in Eq. (1) are as shown in Figs. 1 and 2.

Consider first the term $(L\Sigma T_N/A_R)$ in Fig. 1.

The value of the curve in the region below 1 GHz is determined by the effective external man-made noise level in an urban environment. The noise is primarily due to automobile ignition and high voltage transmission. Measurements taken for NASA as part of two voice broadcast satellite feasibility studies[4,5] indicated that the level has not changed radically in the last 15 or 20 years. Thus, this part of the curve is probably not going to change over the next 10 years. Also there have been indications that the r.f. noise level in urban areas of emerging nations may be well in excess of that in the USA due to improper maintenance of electrical equipment and the use of old automobiles. While r.f. noise abatement does not seem to be amenable to a solution at present, more sophisticated methods must be found to assess and characterize the noise than are now used. As part of our program at Lewis Research Center we have contracted an investigation of the use of aircraft in measuring the level and characteristics of radio frequency noise.

The section of the curve between 1 GHz and 4 GHz is determined primarily by the noise factor of the front end of the antenna mounted receiver unit. In inexpensive devices today this noise factor varies from 13 db at 1 GHz to 20 db at 15 GHz. The state-of-the-art is from 7 db at 1 GHz to 14 db at 15 GHz. In this frequency region and above the NASA is attempting to assess the costs and technological factors of small, integrated circuit type antenna mounted units.

The values of the section of the curve above 4 GHz is not determined by atmospheric losses as might be expected, but by a limitation on the receiving antenna beamwidth, and thus receiving antenna area. This is due to the error in properly pointing and maintaining pointed an inexpensive antenna. A change in this beamwidth limitation (in this case 2^o) will shift the line to the right or left. The value of the beamwidth limitation of course will also be dependent on the mission.

To increase number of applicable missions of broadcast satellites at the higher frequencies an effort will be made to assess the beamwidth limitation and to decrease the value with the aid of better inexpensive antenna mounts and small and inexpensive integrated circuit type steered antennas.

It should be remarked here that a more subtle trade-off may also come into play. If the receiver beamwidth gets very small then the satellite station keeping must become better. The result will be that the weight for station keeping of the satellite will go up.

Let us now consider the second bracketed term in Eq. (1), $(S/N)/L_T$, which is shown in Fig. 2. The shape of this curve merits some explanation as to its generation. The apparent improvement for an AM signal is primarily due to the fact that the power level desired is the average power level while the commonly used signal-to-noise ratio is the ratio of peak power to rms noise. In generating these curves beyond 1 GHz it has been assumed that there is a bandwidth limitation of 1.25 percent of the carrier frequency due to amplitude and phase nonlinearities in the receiver. Thus with increasing frequency the modulation index increases to fill this bandwidth until the FM threshold is reached for the given signal-to-noise ratio, beyond which point the bandwidth and modulation index are constant. Because of this bandwidth limitation it is more efficient to use AM modulation below 1 GHz.

The value of 35 db for S/N shown in equivalent to a picture of "fine" TASO grade which is superior to that of the averaged received television picture. The value of 40 db is equivalent to and "excellent" TASO grade and noise is not apparent for most viewers above this level.

Receiving systems and satellite transmitters which have sufficient phase linearity over a larger frequency range to allow a larger percentage bandwidth would move the curves in the region of 1 to 2 GHz toward the right thus increasing the improvement at lower frequencies. Use of systems with FM feed back would lower the threshold levels allowing for higher modulation indeces at a given signal-to-noise ratio.

Combining values in Figs. 1 and 2 and multiplying by the proper constants for a geostationarey satellite the curves in Fig. 3 are obtained. In calculating the values for these curves a 3 db loss was taken for circular to linear polorization loss at the antenna, and a 3 db loss for reception at the halfpower beamwidth point.

Shown in the figure are the values which would be obtained using fairly inexpensive receivers available today, inexpensive receiver systems reflecting the state-of-the-art of today and the near future, and receiver systems of the more advanced or expensive type.

The effect of technology gains in the receiver and receiving antenna is to decrease the necessary power level, especially in the region of the minimum, and to extend the width of the minimum to higher and lower frequencies.

It would be interesting to be able to give an accurate value as to what would be the retail cost for a mass produced antenna and antenna pre-amplifier/demodulator that would achieve the values given in Fig. 3. From some integrated circuit manufacturing sources we have received informal estimates as to these costs. In addition a preliminary survey study was made a few years ago for NASA[6]. Given in Fig. 4 are rough estimates of the costs from the preliminary information. There is a fair variation in the values but all are surprisingly low and the NASA is in the process of further assessing the technology and the costs by both in-house and contract investigations.

SPACECRAFT TECHNOLOGY CONFIGURATIONS

Before assessing the technological problems of the spacecraft it is instructive to first look at the sizes and weights of some typical spacecraft configurations to gain a feeling for the relative magnitudes of the problems. Assume that the mission of the satellites is to broadcast to the receivers discussed above and that the receivers are distributed over an area the size and shape of the central time zone (3^{o} beamwidth). Then the characteristics of the satellites at three frequencies might be those shown in Figs. 5, 6, and 7.

As shown in Fig. 5 to broadcast to the receivers at UHF (VSB) the satellite would require at least 3 KW average transmitted power. The antenna would be between 22 and 27 foot diameter and weigh between 100 and 250 pounds. The necessary power would be provided by a sun oriented solar array with an output power between 9 and 15 KW and a weight of between 1000 and 2000 pounds. The total satellite weight would be between 3000 and 4500 pounds. This satellite is large, heavy, and ungainly.

The satellite to broadcast at 2.5 GHz with FM modulation is shown in Fig. 6. This is near the minimum of the ERP curve shown in Fig. 3. The satellite would have a transmitter output power of 200 watts per channel and a prime power of between 0.6 and 1.2 KW depending upon the technology level. The antenna would have a diameter of about $9\frac{1}{2}$ feet and would be deployed as a single unit. The weight of such a satellite would be between 800 and 1200 pounds.

The satellite to broadcast to receivers at 8.2 GHz is shown in Fig. 7. For this mission the required satellite transmitted power would be 500 watts per channel and a resulting prime power of between 1.0 KW and 2.0 KW for one channel operation depending upon the technology level. The antenna shown is a circularily polorized array which is mechanically steered. The array has a diagonal width of 3 feet. This satellite would weigh between 900 and 1300 pounds.

Consider now the spacecraft subsystems. The major chain of spacecraft subsystems is shown in Fig. 8. The uplink power is received, translated to the down link frequency and modulation, and amplified for transmission. The transmitting amplifier is powered by the solar array through the power conditioning equipment. The heat generated due to amplifier inefficiency is rejected. In addition the receiver information is used in an interferometer subsystem to supply direction and position information to the attitude control and station keeping systems and the antenna steering system.

Antenna. - The major problems associated with the spacecraft transmitting antenna are: packaging for launch, weight, deployment, structural stability, beam guidance and shaping, interference, and high power handling. These problems all become more critical as the antenna size and output power increase with lower frequencies (Figs. 5, 6, and 7).

The types of antennas being considered for space missions can be divided into two typical categories. First are antennas of fairly high specific weight[7,8] (approximately 0.3 pounds per square foot of aperature) which have high surface tolerances, good structural stability, but low packaging ratios. Typically these antennas deploy in petal fashion as shown in Fig. 9. Second are antennas which have low specific weights[4,5,9] (0.05 lb/ft^2), high packaging ratios, but low surface tolerances and structural stability due to the use of flexible mesh surface in conjunction with a minimum of support structure.

At the UHF frequencies the large antennas for most missions must be packaged into a 10 foot diameter shroud and compete for space with a high power solar array. Because of this and the weight savings the antennas of the second category look very attractive for low frequencies. However, in some cases it will be necessary to minimize the power spill-over into regions outside the main beam. This may necessitate lowering the antenna pattern near side lobe level to as low as 40 db below the main beam level. This can only be done with antennas having high surface tolerances, special feeds and good structural rigidity. This, of course, means higher weight and poorer packaging.

At the higher frequencies where neither weight nor size are major problems more sophisticated antenna types will probably be used.[10] At these higher frequencies the antenna pattern shape and level must be highly controlled. In some cases the desire to use more sophisticated antennas such as ones using offset multiple channel feeds may compromise the ability to control the near sidelobe level.

There are additional problems due to high transmitted powers which are not connected directly with the antenna per se but which must also be considered in the antenna design and location. These include: (1) breakdowns in the antenna feed on the antenna surface due to improper outgassing and high field gradients, (2) interference with the uplink signal by the transmitted signal, for it must be remembered that the uplink signal power at the satellite is on the order of microwatts while the output power is in kilowatts.

Transmitter. - The output device of the broadcast satellite amplifier is the major electrical power consumer on the satellite. It is also the major source of heat that must be rejected. It may also be the pacing item of the mission schedule and the determining item of spacecraft useful life.

Present space qualified output devices are limited to powers below 100 watts and efficiencies below 20 percent. There are today working in ground installations many tube types in the frequency and power ranges envisioned for space broadcast applications. However, these tube types must have increased efficiency, different cooling systems, and increased life to become technically and economically practical for satellite use.

Because of the necessity to life test and space quality the devices, the available tube or solid-state module may lag the state-of-the-art by as as much as 5 years. This is especially true to tube output devices where it is necessary to carry life tests over a considerable time span to obtain meaningful data.

Shown in Fig. 10 is a check list of the more promising candidates that could be available in 5 years as a function of transmission frequency and modulation.[11,12] There is a demarkation in types between UHF-AM and higher frequency FM devices. In the following discussion the two ranges will be considered separately.

The output devices listed for UHF-AM modulation are: solid state modules, ceramic triodes, and AM modulated cross field amplifiers (CFA).

Today there are experimental solid state modules in the 800 MHz range with power outputs of 50 watts at efficiencies up to 40 percent. These modules could be joined together in the spacecraft or work as an array of separate radiators on the antenna. The advantages of such a multiplicity of devices are graceful degradation and extension of the heat source. The use of solid state devices will increase in future years as the efficiency and useful frequency increases.

The ceramic triodes as envisioned could have a power of approximately 2 KW joined again in array form for higher power. Such triodes today have efficiencies as high as 60 percent at UHF frequencies but require further development before they can be considered space qualified for a mission of more than 2 years.

The cross field amplifier, which is similar in form and operation to a magnetron, at present is a device used for FM or pulse modulation. The forms of these devices in which the beam is reentrant have very high efficiencies as the power in the beam is reused. The characteristics of these devices are such that they may lend themselves to AM modulation of the beam, in which case a highly efficient AM device is possible. While this technique will require much further investigation the possible results warrant the effort.

At the higher frequencies where FM modulation is used, the traveling wave tube (TWT),[13] the klystron,[14] and the FM-CFA are the most promising devices. The TWT and klystron are linear beam tubes in which the DC kinetic energy of the electron beam is converted to r.f. power. For this type of tube, the efficiency must be raised by increasing the conversion from dc beam power to useful r.f. power and by recovering the remaining kinetic energy of the spent beam as it reaches the end of the tube as useful d.c. electric power rather than as useless heat. This latter can be done by means of more sophisticated collectors.

In all these devices it is most desirable to operate them at their highest efficiency, i.e., at saturation. It may also be desirable to use the device to operate at more than one channel simultaneously. However, by increasing the interaction between the beam and the tube structure to increase the efficiency, harmonics in the output may be introduced when more than one channel is used which will produce seriour distortions in the final picture. This may mean that some compromises as to efficiency may be necessary to obtain a good picture.

Because of the critical effect of the transmitting device on any program using high power r.f. transmission the NASA has begun a cooperative effort among its centers to support research and development in space qualified high power tubes.

Thermal control. - The major problem of thermal control is rejection of the heat generated in the transmitting tubes. The solid state devices present no great problem as they would be dispersed over a large area. On the other hand, the thermal energy generated in a tube may be confined to a relatively small area. The usual method of cooling tubes by pumped liquid systems is out of the question because of weight and low reliability. The use of simple conduction by masses of copper is either too heavy or in many cases physically impossible. The alternates seem to be the use of heat pipes[15,16] which have extremely high effective thermal conductivities or, in the case of TWT's and klystrons, direct radiation from an extremely hot beam collector.[17] Even these methods may not be sufficient for use in the CFA where much of the beam is collected on the r.f. structure. This structure, which decreases in size with increased frequency, may become too fine above the 8 GHz for the installation of proper sized heat pipes for cooling at high powers.

Prime power. - Because of the orbit (geostationary) the required broadcast time (22 hours) and the power levels (less than 30 KW) the only logical choice for prime power for use with a broadcast satellite is the solar cell array.[18] The technological problems of the solar arrays for broadcast satellites are packaging, deployment, weight, and power transfer. These problems become more critical for the higher power UHF-AM missions. The effect of the prime power output for a typical spacecraft upon the weight of that spacecraft can be seen in Fig. 11. Three specific weights of solar arrays are shown which vary from the heavier weights of present arrays, through the 20 watts/lb arrays under development,[19] to the more advanced 30 watt/lb arrays.[20,21] In generating these curves degradation in 5 years life and additional weight for attitude control and stationkeeping have been factored in. At the higher power levels the higher solar array specific weight may mean a slippage into another more costly launch vehicle class.

To repeat again, the solar array is also competing for space with the antenna. However, with the solar array there seems to be no inherent disadvantage in going to the higher power arrays except as will be discussed below under attitude control and station keeping. The newer lighter weight arrays not only package better for launching but probably have a higher deployment reliability due to the use of extensible booms.

The NASA is at present sponsoring a number of studies on light weight arrays which, while not specifically meant for broadcast satellite missions, are applicable to them[19,20,21]. These are mostly centered around light weight foldout and roll out arrays of standard cells. There are also sponsored efforts for the development of thin film solar arrays[22], which could further lower the solar array weight.

Power Conditioning

The power conditioning equipment is the link between the solar array and the output device.

The solid state modules will take low DC voltage so that the construction of the power conditioning equipment for these devices offers few problems. However, for tube output devices high voltages (on the order of 20 kV) are needed which may necessitate new approaches toward construction of space power conditioning equipment. In addition, the power supplied to the tubes must be ripple free and closely regulated as to voltage (for TWT and klystron) or current (for CFA). The FM modulated systems always operate at a constant power level. There is a rather large variation in the UHF-AM system, the peak power being about 3 times the average power. To have the most efficient AM system, the solar array output is sized for the average power and a capacitive storage system is used to accommodate the peak power drain which happens during the video synchronization pulse. The programing will also change the power level and this too must be taken into account. There is thus a trade-off in the AM systems between power storage weight and required solar array power weight.

The power conditioning equipment must also accept input variations due to solar cell degradation and shadow effects.

Attitude Control and Station Keeping

During one day the antenna of the broadcast satellite will rotate 360 degrees with respect to the solar array. Minor adjustments as to vehicle attitude can be made by antenna feed motions. The major problem of attitude control concerns the interaction effects between the motions of solar array following the sun and the motion of antenna following the earth. This problem becomes critical when large light weight and semiflexible structures with low natural frequencies are used for both the antenna and solar array.

The lower frequency broadcast satellites would need little or no station keeping over a 5 year life because the satellite would stay within the broad beam of the receiving antenna. However, at frequencies of 4 GHz and above the satellite would have to be maintained to within 3 degrees latitude and longitude or less. This is well within todays capabilities but a 5 year life would mean a sacrifice of the satellite weight to station keeping if the present systems were used. The effect on the satellite weight of the station keeping specific impulse is shown in Fig. 12 for a typical mission. It is seen that in order to decrease the weight of the on-board station keeping equipment below a high percentage of the spacecraft weight, it is necessary to increase the specific impulse to values above 1000 seconds. One device that can do this is the ion engine. The latest developments with ion engines have shown that they can be built in such a manner that the beam can be deflected allowing the axis of the jet to pass through the center of gravity at the spacecraft, thus simplifying the control problem.

CONCLUSIONS

The broadcast satellite presents no unsolvable problems nor any which are beyond solution using extensions of todays state-of-the-art. To apply this level of technology to a feasible spacecraft system which is also economically practical, requires additional effort in increasing efficiency and reliability while decreasing the weight of spacecraft subsystems.

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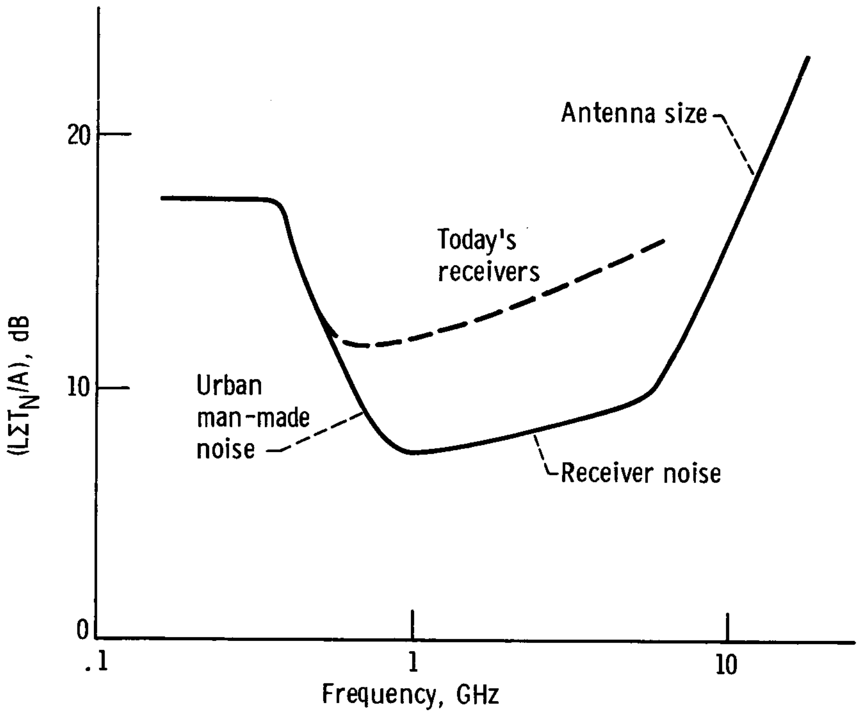

Figure 1. - The receiver variable ($L\Sigma T_N/A$) as a function of frequency for a typical broadcast satellite system.

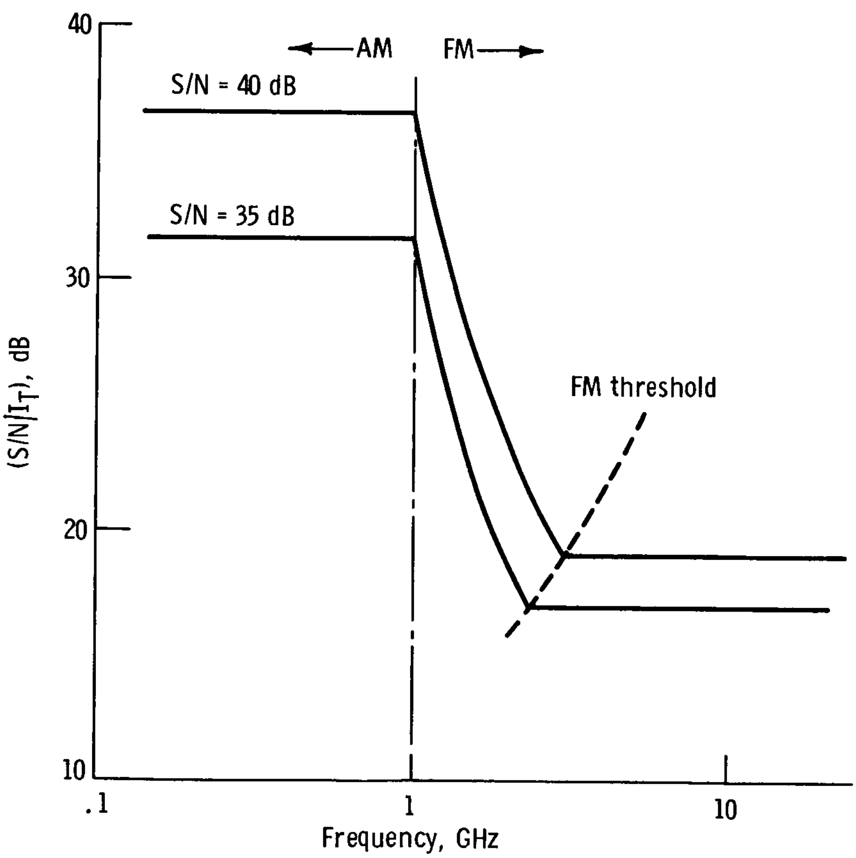

Figure 2. - The improvement variable ($S/N/I_T$) as a function of frequency for typical broadcast satellite system.

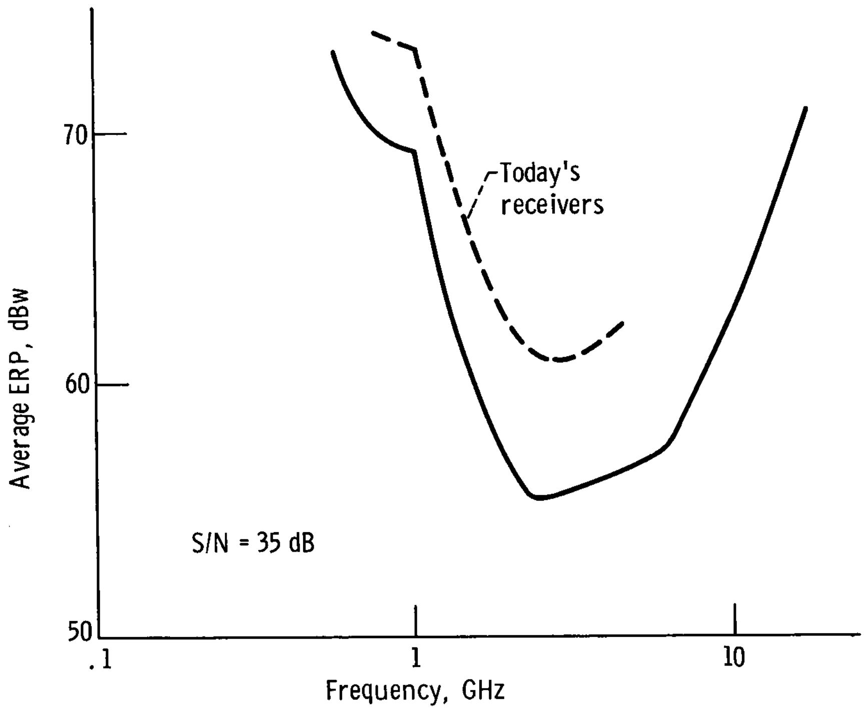

Figure 3. - Transmitter average ERP as a function of frequency for a typical broadcast satellite system.

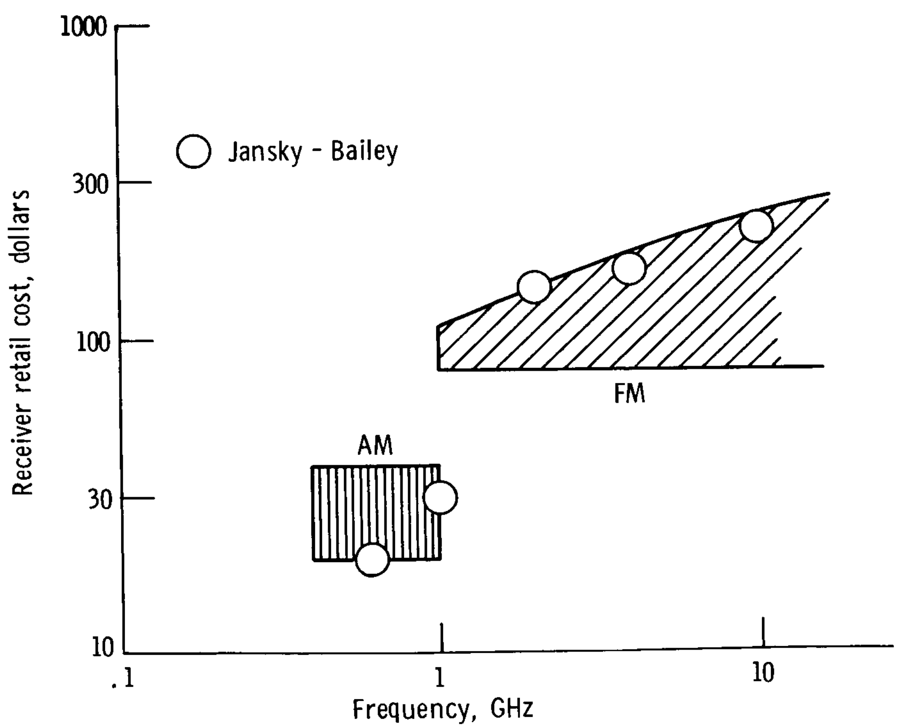

Figure 4. - Estimated retail cost of receiving antenna and preamplifier, typical mission, 10^6 units.

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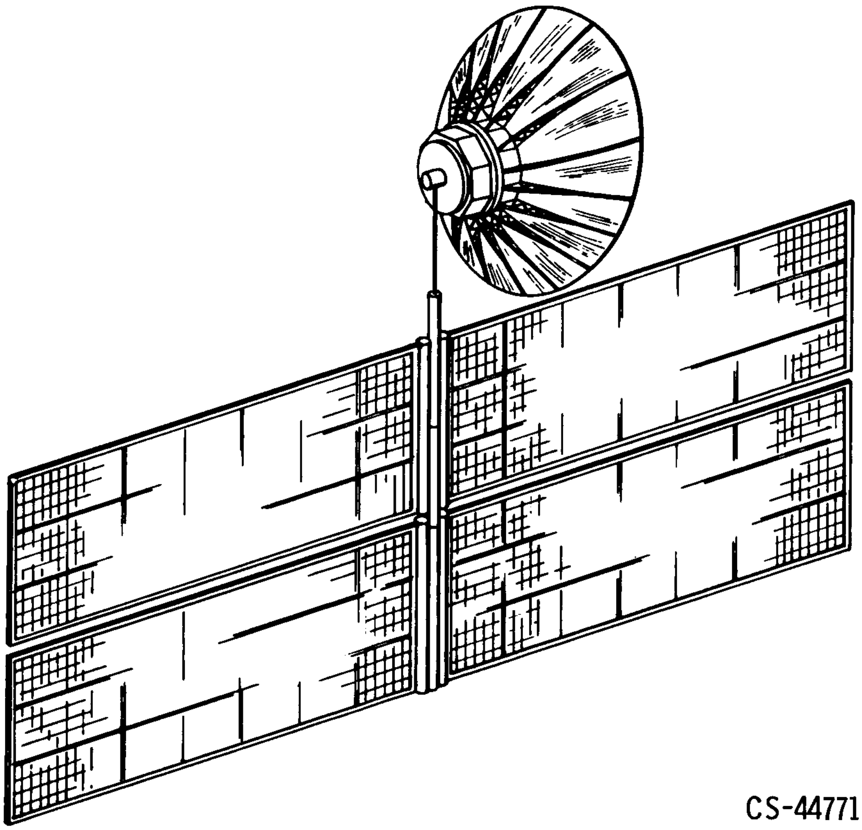

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Figure 5. - Typical UHF broadcast satellite configuration.

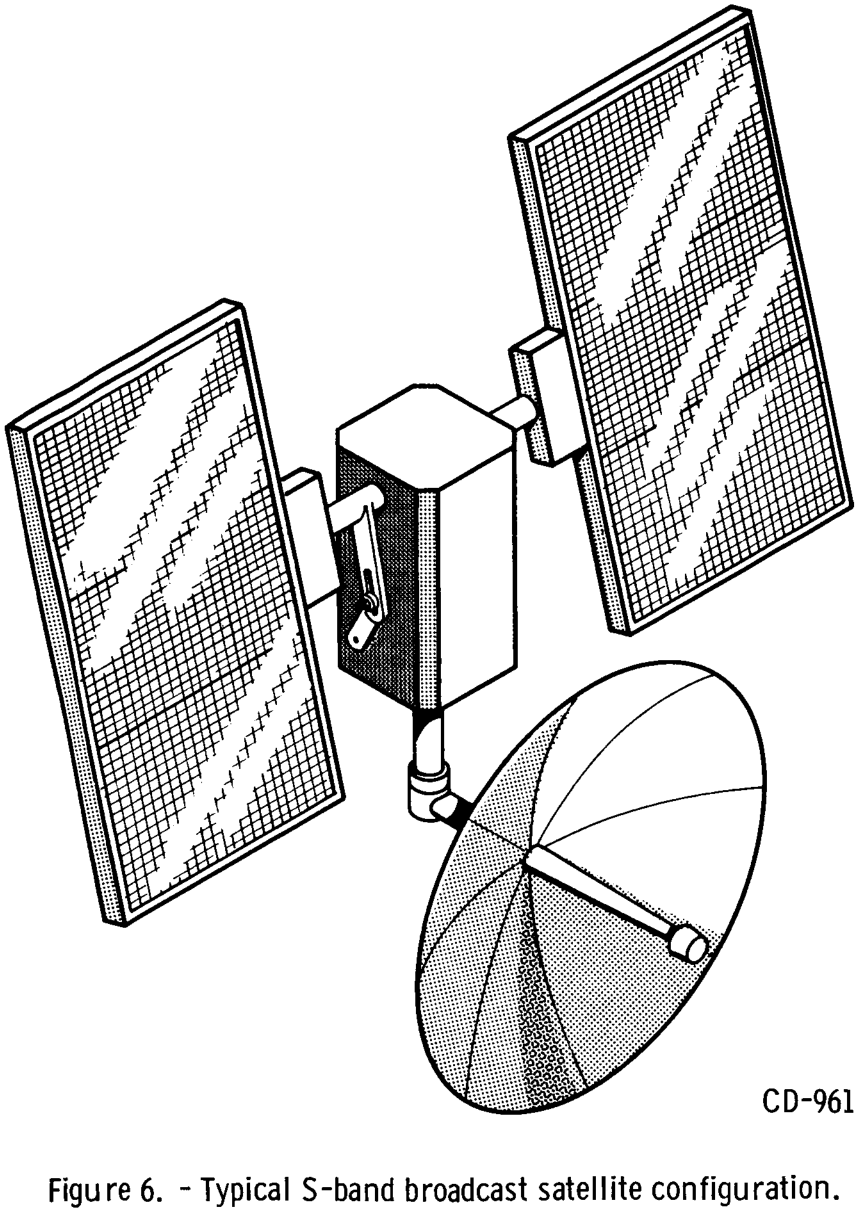

Figure 6. - Typical S-band broadcast satellite configuration.

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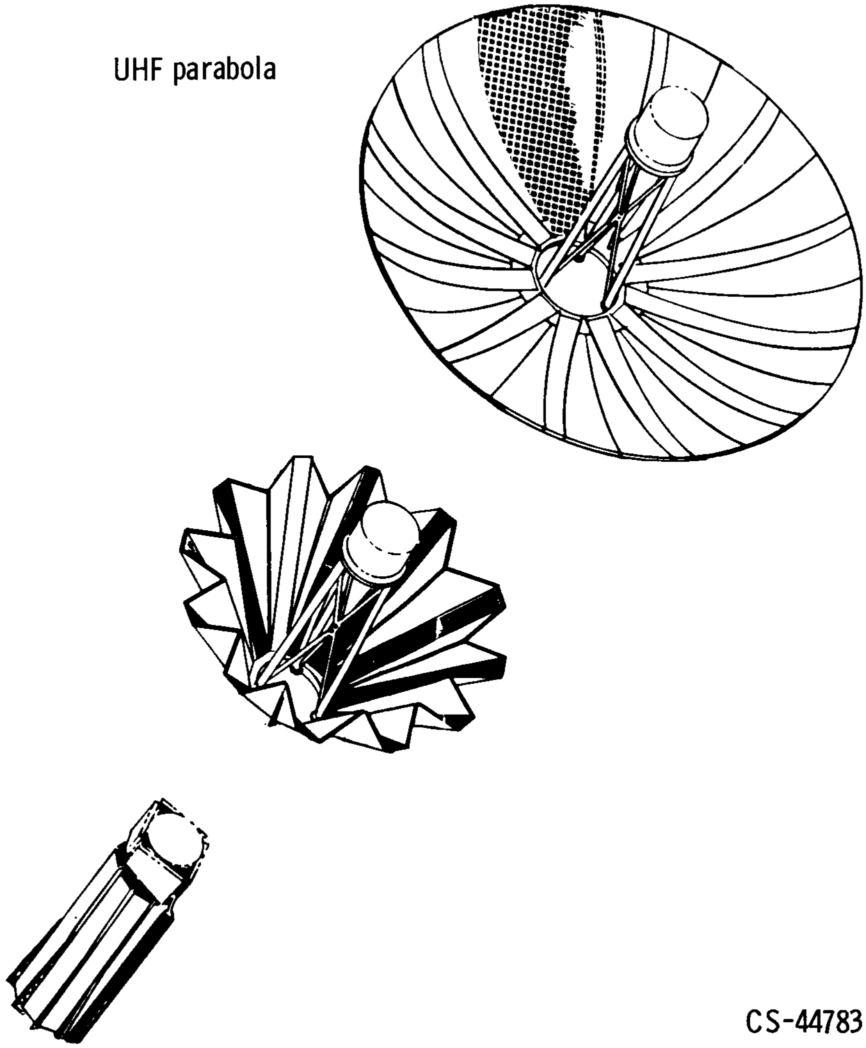

Figure 9. - Deployment of UHF antenna.

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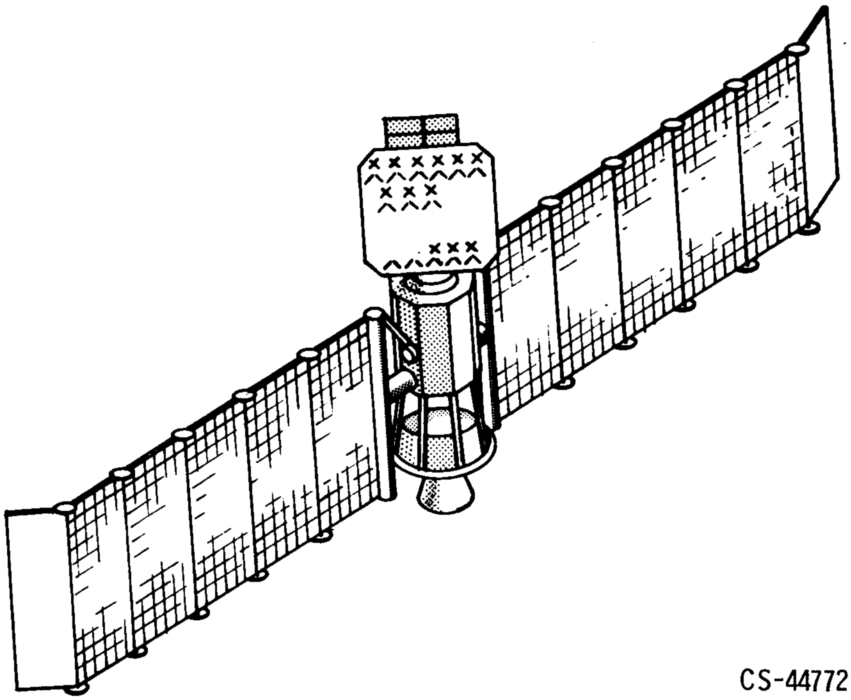

Figure 7. - Typical X-band broadcast satellite configuration.

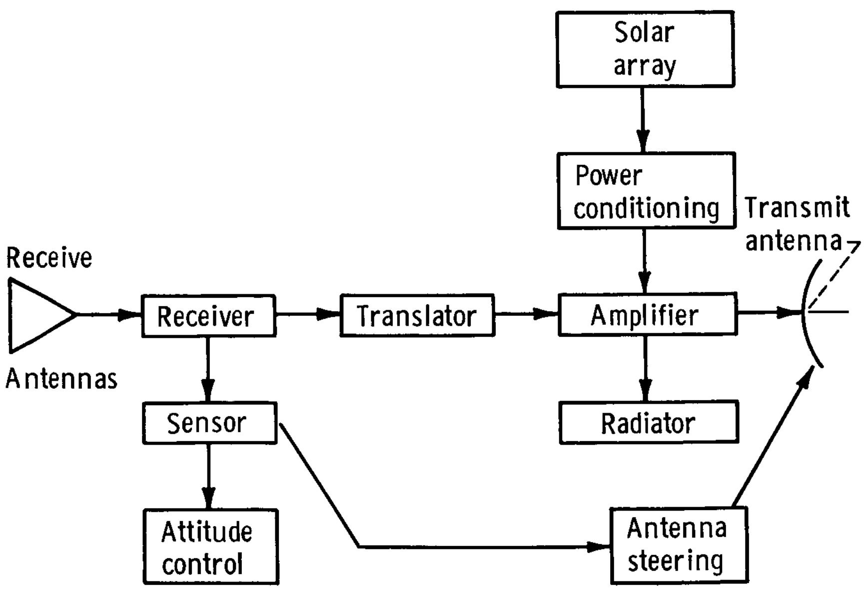

Figure 8. - Major spacecraft subsystems, broadcast satellite.

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Frequency	890 MHz	2.5 GHz	8.2 GHz
Modulation	AM	FM	FM
Solid state	√		
Triode	√		
CFA	√	√	√
Klystron		√	√
TWT		√	√

Figure 10. - Table of candidate devices for transmitter output stage.

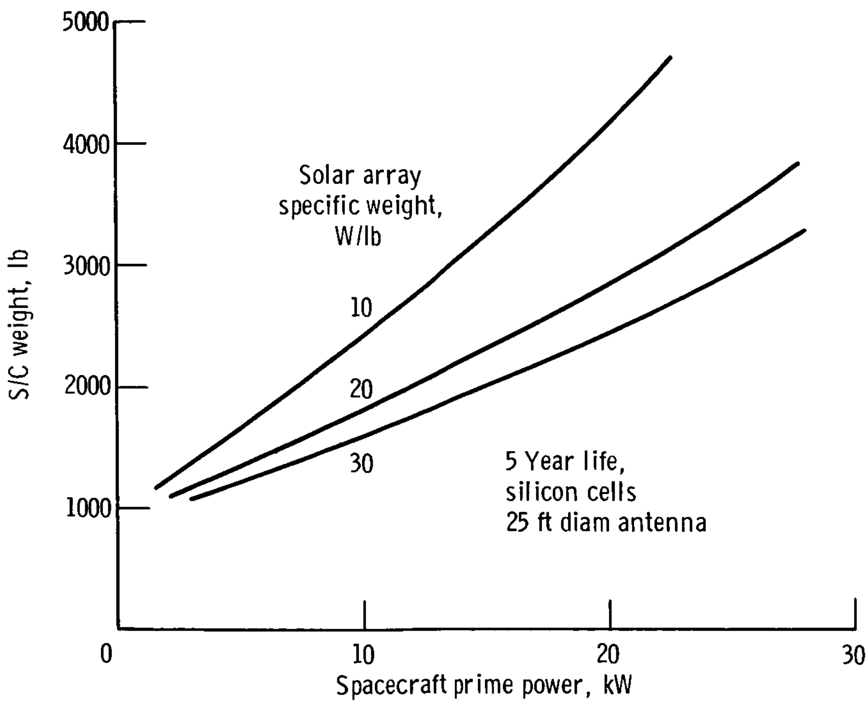

Figure 11. - Spacecraft total weight as a function of prime power and solar array specific weight.

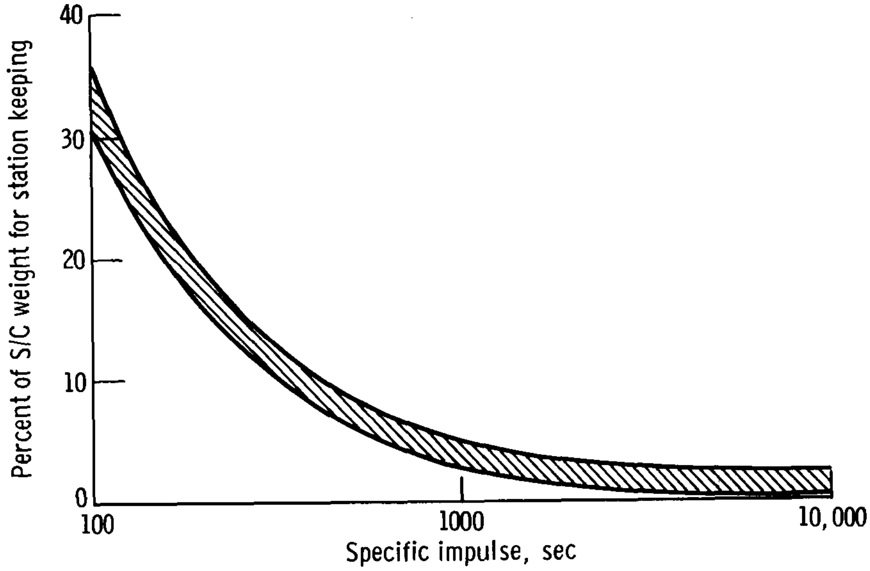

Figure 12. - Weight of station keeping for 5 years life as a function of device specific impulse.

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